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(71) Applicant: INTEGRATED CHEMICAL  
SYNTHESIZERS, INC.  
Rockville, MD 20852 (US)

(72) Inventor: Bard, Allen J.  
Austin, TX 78731 (US)

(74) Representative: Schlich, George William et al  
Mathys & Squire  
100 Gray's Inn Road  
London WC1X 8AL (GB)

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### (54) Chemical reactions using a nanoscale reaction system

(57) A chemical reaction is carried out using at least one reactant and a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising providing a support structure having a plurality of prearranged flow connections; selecting the plurality of reaction system components; assembling the plurality of selected reaction system components onto the support structure; and performing the predetermined chemical reaction to form one or more reaction

products. The plurality of reaction system components are selected and arranged to accommodate the predetermined chemical reaction. Another method comprises assembling the plurality of reaction system components; providing the at least one reactant to one or more of the reaction system components; reacting the at least one reactant in one or more of the reaction system components such that one or more reaction products are formed; and collecting the one or more reaction products.

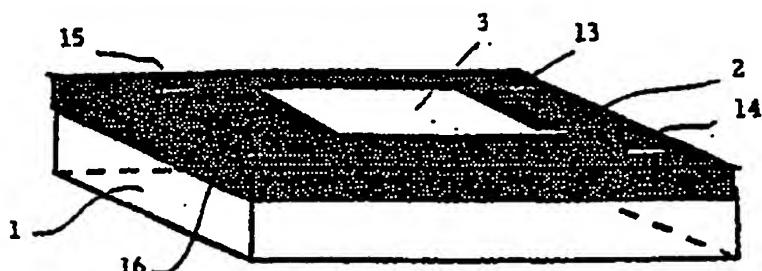
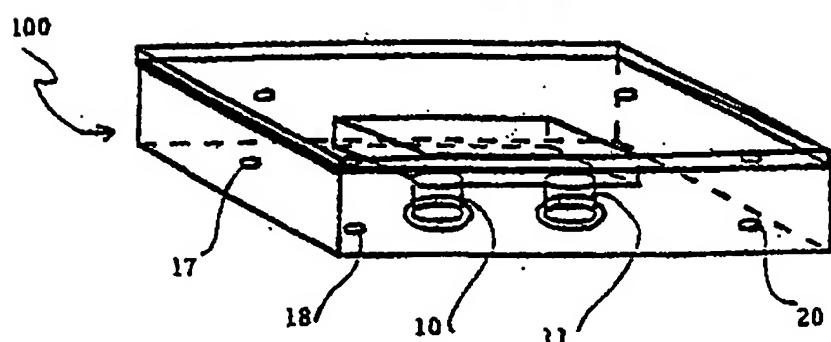
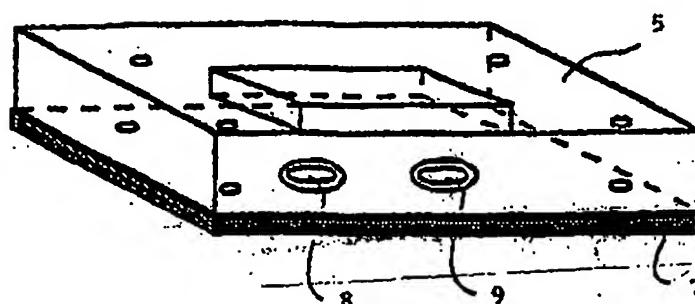
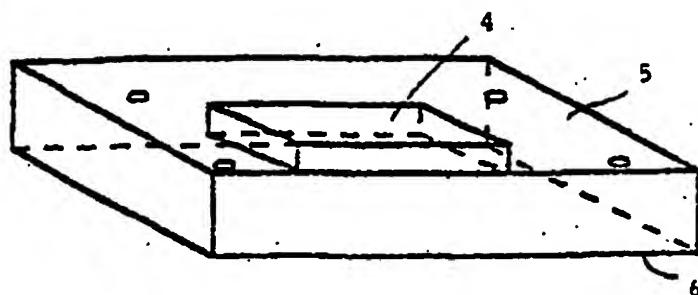


FIG. 1a

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**Description****FIELD OF THE INVENTION**

5 [0001] This invention relates to an improved method and apparatus for continuously synthesizing chemical compounds under controlled and regulated reaction conditions. More particularly, this invention relates to a modular multi-component system with interchangeable microreactors, that can be used in tandem, series, or individually. Flow and reaction conditions of the modular multi-component system can be monitored to regulate the reaction process and/or create an optimal environment for the synthesis of the desired chemical compounds.

10

**BACKGROUND OF THE INVENTION**

15 [0002] Complex inorganic and organic compounds, e.g., drugs, monomers, organometallic compounds, semiconductors, polymers, peptides, oligonucleotides, polynucleotides, carbohydrates, amino acids, and nucleic acids belong to a class of materials having significant diagnostic, medicinal and commercial importance. Many techniques have been developed to produce these materials. However, the systems necessary to carry-out and prepare or synthesize these complex materials are inefficient, wasteful and often times require reagent quantities far in excess of what is available. This is especially the case in those instances where microliter quantities are involved. The use of conventional substrates requires larger sized systems with the incumbent process control problems. Additionally, reagent or reactant stability must be considered and accurately controlled to render the process efficient in yield and cost.

20 [0003] The production of these complex materials requires a versatile system that can handle different reaction and separatory schemes. Most synthesizers provide only for a single type of reactor, e.g., electrochemical, catalytic, solid phase support, enzymatic, photochemical, or hollow chamber.

25 [0004] For example, U.S. Patent No. 4,517,338 to Urdea teaches a system for sequencing amino acids that uses one or more elongated tubular reaction zones. The reactors for each reaction zone are similar in structure with an internal diameter (I.D.) of a 0.1 to 1.0 cm. Each of the reactors needs a glass frit to support the solid-phase material.

30 [0005] U.S. Patent No. 4,960,566 to Mochida relates to an automatic analyzer for conveying reagent coated capillary tubes along process lines where reagents are added, reacted and analyzed. The Mochida patent indicates at Column 3 that the inner diameter of the capillary tubes appears to be no smaller than 0.95 mm. The process of Mochida provides for serial processing of reaction tubes of a common design. Independent temperature control of parallel tubes and modularity are not provided.

35 [0006] U.S. Patent No. 4,276,048 to Leaback teaches capillary size reaction containers for volumetric transfer of fluids to a microtitre tray. The system is essentially batch-like and does not involve continuous flow or automatic valving to selectively direct the flow of a particular reagent to one reaction column as opposed to another to provide for amino acid sequencing within the tube.

40 [0007] U.S. Patent No. 5,176,881 to Sepaniak et al. teaches a fiber optic-based regenerable biosensor that uses a capillary feed mechanism.

45 [0008] U.S. Patent No. 4,362,699 to Verlander et al. relates to high pressure peptide synthesizers and uses a plurality of reservoirs that communicate via a switching valve to a reactor 90. The Verlander system was designed to overcome the limitations of the Merrifield system which apparently had a limitation of synthesizing peptides having no more than 10 amino acids. The system can also include a mixer upstream of the reactor to mix the protected amino acid solution and the appropriate activating reagent. Column 6 lines 3-12. The system is automated and the reactor column contains a polystyrene resin which is derivatized with a protected amino acid.

50 [0009] U.S. Patent No. 4,458,066 to Caruthers et al. teaches an amino acid synthesizer and uses a plurality of reagent reservoirs connected via a manifold to a tubular reactor. The reactor column 10 includes a solid silica gel matrix derivatized for the sequencing operation and, via a valve can be communicated to a UV detector 58. The reactor is taught to be sized for a 1 ml. volume.

55 [0010] U.S. Patent No. 4,728,502 Hamill relates to an amino acid sequencer that utilizes a plurality of stacked disks each having a plurality of chambers and resulting in a plurality of parallel columns. Although the contents of each chamber of each disk are removable, the respective columns formed by a series of chambers in the stacked disk are not.

60 [0011] U.S. Patent No. 4,961,915 to Martin relates to a DNA sequencing system. A rotatable turntable conveys fluids along narrow channels that are open on an upper end. This allows individual dispensing of additional reagents along the length of the channel. The Martin patent does not provide a continuous flow valved reaction system or direct in-line valving to control reagents directly to one or more channels. In addition, the grooves or channels are in a common base and replacement or scale up is not possible.

65 [0012] The object of the subject invention is to provide an Integrated Chemical Synthesizer (ICS) system that is modular in design and provides for continuous flow operation. The modular nature of the ICS system allows for the use of one or more of the same type of reactor, or a variety of different types of reactors, each having microliter capacity.

The reactors of the ICS system are capable of being used individually, together, and interchangeably with one another and can be of the thermal, electrochemical, catalytic, enzymatic, photochemical, or hollow chamber type. The modular nature of the system, component parts, e.g., the reactors, flow channels, sensors, detectors, temperature control units, allows easy replacement and/or interchangeability of the component parts and provides a versatility not offered by existing systems.

[0013] The ICS system provides for uniform temperature control for continuous flow reactors under elevated pressures. This allows for precise control of residence time within a reaction zone. ICS synthesizers would thus exhibit a number of advantages when compared to conventional systems of larger size. Heat transfer, which depends upon the ratio of surface area (A) to volume (V), would be much better for the smaller reactors. This is a major advantage, for example, in capillary zone electrophoresis compared to large scale gel electrophoresis. This configuration also allows faster heat dissipation and faster thermal control.

[0014] The ICS system would not only present better control of reaction conditions, but it would allow for quenching reactions at certain stages to prevent further reaction. The ICS system would also, due to its modular nature, provide for serial placement of reactors to allow controlled sequential reactions of intermediates. Moreover, it should be much easier to scale-up reactions based on the ICS approach because one would simply add additional modules of exactly the same type to increase output. For industrial synthesis, the ICS approach would eliminate proceeding from a bench scale reactor through a variety of different pilot plant configuration to a full-sized reactor.

[0015] Moreover, the inherent redundancy of multiple parallel ICS reactors implies fewer operational problems with the failure of a few reactors, especially if the system is set up for easy replacement and repair of a single ICS line. As a result, such systems are probably inherently much safer. The rupture of a single ICS reactor, even at high temperature and pressure, would cause negligible damage since the total volume and amounts of reactants released would be small. This would be especially beneficial when carrying out reactions under extreme conditions, e.g., the high temperatures and pressure in supercritical water and other fluids. Overall the ICS system should result in better yields of products with less waste and disposal problems because of better control of reaction variables.

[0016] As a result of the ICS modular system, the problems of inefficiency, lack of versatility, down-time, reagent/reactant waste and excessive cost have been overcome.

## SUMMARY OF THE INVENTION

[0017] Accordingly, the present invention provides a novel system for synthesizing chemical compounds. The system of the present invention can also synthesize compounds under a variety of process conditions, e.g., uniform temperature in a continuous flow reactor under high pressure, non-uniform temperatures and high pressure.

[0018] In accordance with one aspect of the present invention a modular multicomponent system is provided. The system, e.g. a kit, provides a reaction system capable of handling a variety of reactions by using a reactor unit having a reaction chamber with an I.D. of from about 1  $\mu\text{m}$  up to about 1mm, and more preferably 1-100  $\mu\text{m}$ . Specifically, a modular "chip" type reactor unit is formed by applying a photoresist layer onto an upper surface of a  $\text{SiO}_2$  or Si substrate and forming a reactor design thereon. The reactor design is developed and etched with acid to form a reactor chamber having an ID less than 100  $\mu\text{m}$ . The chamber is covered and the unit mounted on an assembly board containing fluid conveying channels, with fastening means, to provide for flow to and from the reactor chamber.

[0019] In accordance with another aspect of the present invention, a modular multicomponent system containing a plurality of interchangeable reaction vessels, alike or different, in parallel or series, and capable of handling reaction volumes from about 1nL up to about 10  $\mu\text{L}$ , and more preferably 1nL-10  $\mu\text{L}$  is provided.

[0020] In still another aspect of the present invention, both organic and inorganic compounds can be synthesized.

[0021] In yet another aspect of the present invention, a novel system capable of regulating extreme conditions (e.g., supercritical temperatures and pressures) is provided. This system for synthesizing compounds provides a means for avoiding potential explosions and provides a reliable method for heat dissipation.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0022]

Figs. 1a-1d show a fabricated chip type reactor unit for the ICS modular system.

Figs. 2 illustrates an exploded view of a chip type reactor unit and the fluid delivery flow channels of an assembly board according to the present invention.

Fig. 3 is an exploded view of one embodiment of the ICS system.

**Fig. 4** shows an exemplary ICS system with fluid control and computer interfacing according to the subject invention.

**Fig. 5** is a flow chart for preparing t-BuCl using the subject invention.

**Fig. 6** shows a flow chart for photochemical conversion of dibenzylketone using the ICS system of the subject invention.

**Fig. 7** is a flow chart illustrating electrochemical reduction of benzoquinone according to the present invention.

**Fig. 8** is a flow chart for multiphase membrane reactor conversion of benzylpenicillin to 6 amino penicillanic acid (6-APA) using the ICS system.

**Fig. 9** is a flow chart for converting n-C<sub>7</sub>H<sub>16</sub> to toluene using the subject invention.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0023] The present invention is broadly directed toward a total modular system that can use a plurality of replaceable and interchangeable cylindrical or rectangular reactors in combination with a mass-based sensor. Generally, the ICS system can include (1) fluid flow handling and control components; (2) mixers; (3) reaction "chip type" units; (3) separatory devices; (4) process variable detectors and controllers; and (5) a computer interface for communicating with a master control center.

[0024] The ICS system may also include a support structure for detachably retaining the various components of the system. The support structure can be of the "assembly board type" that will contain pre-arranged flow channels and connector ports. The desired components of the system can be fastened into these connectors by pins. The flow control components that make-up the ICS system can include pumps, flow channels, manifolds, flow restrictors, valves, etc. These components will have the necessary fittings that allow them to be sealed with the pre-arranged or selectively located flow channels or connectors. The flow system can also include detachable mixing devices, e.g., static or ultrasonic, some of which can be "chip like" in design. The reaction units, whether "chip like" or not, can be of the thermal, electrochemical, photochemical, pressure type and be rectangular or cylindrical in shape.

[0025] The separatory components can provide for membrane separation, concurrent or countercurrent flow extraction, chromatographic separation, electrophoretic separation, or distillation. The detectors can include electrochemical, spectroscopic or fluorescence based detectors to monitor the reactants, intermediates, or final products.

[0026] The ICS system can include a plurality of individual, detachable reaction units. With a plurality of units, one of the reaction units may be structurally different and capable of permitting a different chemical process of being performed. For example there may be thermal and photochemical units or electrochemical, thermal and pressure units. The ICS system can also include a detachable separation chamber, and an analyzer capable of monitoring and/or controlling a process variable. More specifically, a typical embodiment utilizes flow channels, a flow mixer, at least one electrochemical reaction chamber, an electrophoretic separation chamber, and an electrochemical analyzer.

[0027] In accordance with the preferred embodiment of the present invention, an apparatus for achieving the synthesis described above is illustrated in Fig. 1-9.

[0028] The basic concept of the subject invention is to produce a modular system, with components (reactors, separation chambers, analyzers, etc.) that are inexpensive and easily assembled. The subject invention can be assembled on a flow channel assembly board in the same way integrated circuitry chips and other electrical components are assembled on a circuit board. In the ICS system various reactors, analyzer(s), e.g., "chip units," are put together on an "assembly board". Two approaches to assembling such systems would be (a) custom design chips and assembly boards or, (b) the current capillary high pressure liquid chromatography (HPLC)-capillary zone electrophoresis (CZE) approach with microbore tubing (silica, stainless steel) and various connectors, injectors, pumps, etc. In case (a) the chips could be made from silica (SiO<sub>2</sub>)/glass, silicon (Si)(as integrated circuit chips), polymers (plastic), and/or metal (stainless steel, titanium).

[0029] An example of fabricating a chip unit 100 according to the invention is shown in Figs. 1a-1d. With reference to Figs. 1a-1d, a substrate of SiO<sub>2</sub> or Si is designed to include a rectangular reaction chamber 4. The chamber 4 is formed by photolithographic processes such as those currently used for integrated circuits and circuit boards. A photoresist layer 2 is deposited on the upper surface 6 of the SiO<sub>2</sub> or Si block substrate 1 and, the desired pattern 3 is formed in layer 2 by exposure to the proper image and development techniques. The rectangular reactor chamber 4 is formed by etching the preformed pattern into the substrate, e.g., with HF for SiO<sub>2</sub> to the extent necessary to form a chamber having the desired volume. For complex structures, multiple photolithographic processes may be necessary. Flow channels for the reactor are similarly fabricated using photolithography from the other side of the substrate. A

second photoresist layer 7 is placed on lower surface 6, exposed to form port openings 8 and 9. Thereafter, channels 10 and 11 are formed to provide flow communication to reactor chamber 4. Finally, a cover 12 is attached to close the upper surface 5 to form a top of the reactor 4 and produce the finished chip. Photoresist layers 2 and 7 also include a plurality of patterns 13-16 and 17-20 formed thereon so that through channels for fastening pins can be formed. The reactor could also be fabricated at one time, alternatively, with plastic materials, by injection molding or casting techniques. Micromachining (e.g., using the scanning tunneling microscope or scanning electrochemical microscope) of metals and semiconductor substrates could also be used to make the modular units of the subject invention.

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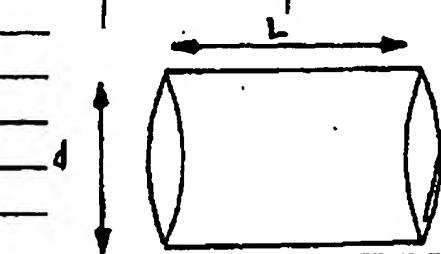
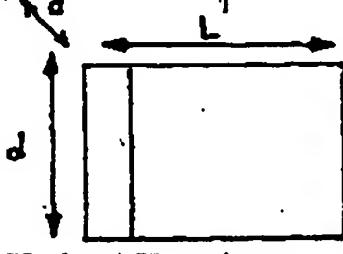
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Table 1 shows volume parameters for various ICS reactors.

## 5 VOLUMES ICS REACTORS

Calculation of ICS Reactor Volumes									
Cylindrical reactor, $V = \pi d^2 L / 4$			Rectangular reactor, $V = d^2 L$						
d (μm)	L (μm)	V (μL)	d (μm)	L (μm)	V (μL)				
1	10	7.85E-09	1	10	1.00E-08				
1	100	7.85E-08	1	100	1.00E-07				
1	1000	7.85E-07	1	1000	1.00E-06				
1	1.00E+04	7.85E-06	1	1.00E+04	1.00E-05				
10	10	7.85E-07	10	10	1.00E-06				
10	100	7.85E-06	10	100	1.00E-05				
10	1000	7.85E-05	10	1000	1.00E-04				
10	1.00E+04	7.85E-04	10	1.00E+04	1.00E-03				
100	10	7.85E-05	100	10	1.00E-04				
100	100	7.85E-04	100	100	1.00E-03				
100	1000	7.85E-03	100	1000	1.00E-02				
100	1.00E+04	7.85E-02	100	1.00E+04	1.00E-1				
1000	10	7.85E-03	1000	10	1.00E-2				
1000	100	7.85E-02	1000	100	1.00E-1				
1000	1000	7.85E-01	1000	1000	1.00E+00				
1000	1.00E+04	7.85E+00	1000	1.00E+04	1.00E+01				
1 μm = (1e-4) cm		1000 μm = 1 mm							
1 μm * 3 (1e-9) μL		1E4 μm = 1 cm							
 									
1 mL = (1e-3) μL									
1 μL = (1e-6) μL									
1 aL = (1e-9) μL									

65

[0030] The different kinds of chip units produced according to the subject invention could then be connected to the assembly board containing the desired flow connections (Fig. 2) and also (not shown) electrical connections to elec-

trodes, heaters, etc. Fig. 2 uses O-rings 40 and 41 (Teflon, Viton) to connect the chip channels 10 and 11 to the corresponding channels 50 and 51 on assembly board 20 and pins 30-37 (or clips) to hold the chip to board 20.

[0031] Fig. 3 shows an assembly of several different chips on a single board with interconnections. In Fig. 3 units 100, 60, and 70 are respectively a reactor, a separator and an analyzer. The housings for separator 60 and analyzer 70 are formed in a manner similar to that of reactor unit 100 described above, but include the requisite, structures and components to perform the designated process, e.g., separation, analysis.

[0032] In Fig. 3, pins 30-33 connect the units 100, 60 and 70 to assembly board 80 containing channels 81-84 therein. Channels 81 and 82 respectively communicate with channels 10 and 11 in reactor unit 100. Similarly, channels 82 and 83 communicate with the corresponding channels in unit 60 and channels 83 and 84 communicate with the channels in unit 70.

[0033] Alternatively capillary tubing for reactors, detectors, etc., following current HPLC-CZE practice, sized in accordance with the subject disclosure may be assembled on a support board in a similar manner (not shown).

[0034] For capillary tubing, connectors, pumps, etc., using the capillary HPLC approach can be obtained from manufacturers, such as, Valco, Swagelok, and Waters. Specialized materials useful in the subject invention reactors and separators can be made from Nafion (ion-exchange) hollow fibers and are manufactured by DuPont.

[0035] If a glass substrate is used for the "chip" units, the walls are already  $\text{SiO}_2$ . If a Si substrate is used,  $\text{SiO}_2$  can be formed by oxidation in air under controlled temperature conditions. For metal substrates, e.g., Ti, a protective and insulating film ( $\text{TiO}_2$ ) can also be formed by air or anodic oxidation. It is also possible to coat the walls of the tube with catalyst particles, organic films for separations, etc.

[0036] Fig. 4 includes an assembly board schematically showing the "chip" type processing units of the subject invention. The assembly board includes a reactor R formed in a manner similar to unit 100 above, but includes a heat transfer system. The reactor R communicates with a chip type mixer  $M_x$  at the upstream end and a chip type detector  $D_1$ , e.g., unit 100, at the downstream end. The detector  $D_1$  communicates with a chip type separator, e.g., unit 60, which in turn is in fluid communication with a second chip type detector unit  $D_2$ , e.g., unit 70.

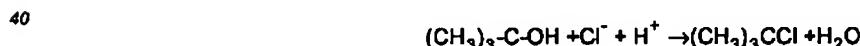
[0037] The system of Fig. 4 operates as follows: reagents A and B via pressure actuated pumps  $P_A$  and  $P_B$ , and valves  $V_A$  and  $V_B$  sequentially or simultaneously flow to the mixer  $M_x$ . If isolation of a reagent is necessary, after reagent A is fed to mixer  $M_x$  and discharged to the reactor R, a wash fluid W is conveyed via pump  $P_w$  and valve  $V_w$  to the mixer  $M_x$  and discharged. Signals from detectors  $D_1$ ,  $D_2$ , thermocouple TC, and flowmeter FM are transmitted to the computer through Interface 90 to control the flow of reagents A and B and temperature, or any additional reagents according to the process to be performed by the subject invention.

[0038] Having now generally described this invention, the following examples are included for purposes of illustration and are not intended as any form of limitation.

#### Example 1

35 Thermal conversion of t-butanol to t-butyl chloride

[0039]



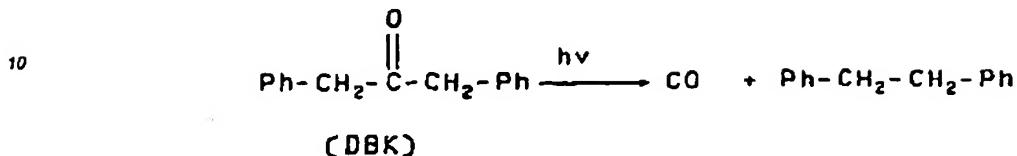
[0040] With reference to Fig. 5, solutions of concentrated hydrochloric acid 201 and t-butanol 202 are metered through pumps 203, 206 and valves 204, 207 to a mixer 205 to the reaction chamber 208. Temperature in the reaction chamber 208 is controlled via a heating/cooling system 215 on the assembly board, e.g., 80, to maintain the reaction temperature (measured by a thermocouple) at about 30-40°C. The two phases that form are separated in the separator chamber 209 and further purification of t-BuCl can be accomplished, if desired, by distillation at 50°C in chamber 213 with product being withdrawn via line 214. HCl and  $\text{H}_2\text{O}$  are withdrawn via line 210 and waste is discharged via line 212.

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**Example 2****Photochemical conversion of dibenzylketone**

5 [0041]

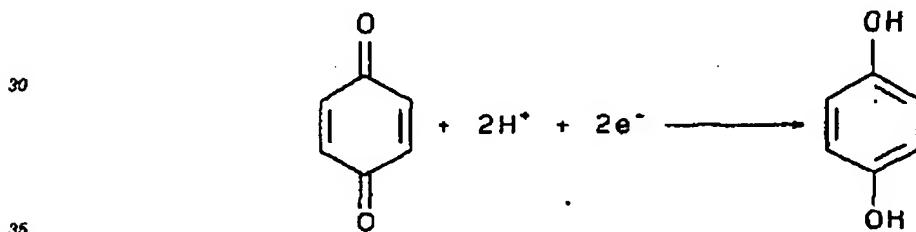


15 [0042] With reference to Fig. 6, dibenzylketone in benzene 301 (0.01 M) is metered via 302 and 303 into the photochemical reaction chamber 304 with at least one transparent wall, where it is irradiated with light 307 from a 450 watt xenon lamp 305 via filter 306. The CO produced 310, in the reaction 309 is vented and the bibenzyl product is purified, if desired, through a chromatographic separator 308 and withdrawn through line 309.

20

**Example 3****Electrochemical reduction of benzoquinone**

25 [0043]



35 [0044] In Fig. 7, an acidic aqueous solution of benzoquinone (0.1 M) 401 is metered (402, 403) into the cathodic chamber 416 of the electrochemical reactor 415. This chamber, e.g. outside a Nafion hollow fiber tube containing the Pt anode and the analyte, contains a carbon or zinc cathode. Anode 408a and cathode 408b are connected to a power supply 407. The current density and flow rate are controlled to maximize current efficiency as determined by analysis of hydroquinone by the electrochemical detector 417. Hydroquinone 410 is extracted in extractor 409 from the resulting product stream with ether 414 metered (412 and 413) from ether supply 411. Alternatively, flow in chamber 415 can be directed to the inner anode chamber with the appropriate controls.

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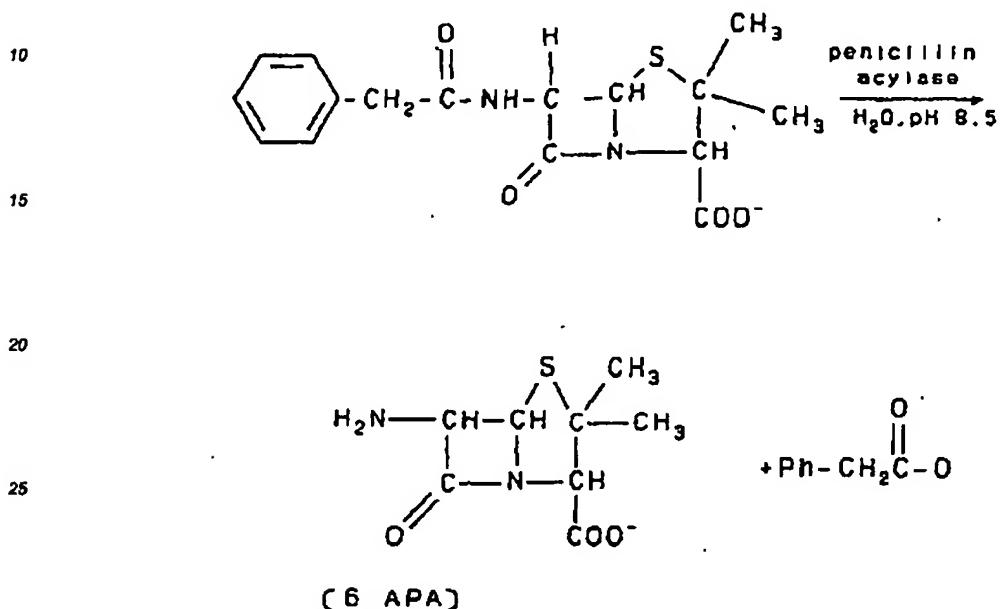
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**Example 4**

## Multiphase membrane reactor conversion of benzylpenicillin (BP) to 6-aminopenicillanic acid (6-APA)

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[0045]

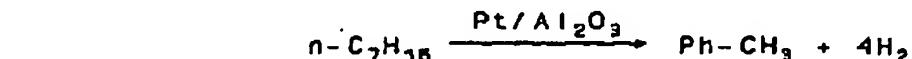


[0046] In Fig. 8, the effluent 501 from a penicillin fermentation reactor containing BP is fed through a filter bank 502 and 503. An aqueous acid 505 is mixed with the filtered BP in mixer 506 and fed to membrane reactor 507. The membrane reactor 507 is preferably a hollow fiber tube 511 on which the enzyme penicillin acylase has been immobilized. The tube also selectively extracts 6-APA (see J.L. Lopez, S.L. Matson, T.J. Stanley, and J.A. Quinn, in "Extractive Bioconversions," Bioprocess Technologies Series, Vol 2, B. Mastiglasson and O. Holst. Eds., Marcel Dekker, N.Y., 1987). The BP is converted on the wall of the fiber and the product passes into the sweep stream inside the fiber where it can be purified by ion exchange 508. The BP stream 510 is recycled back through the reactor.

**40 Example 5**

## catalytic conversion (reforming) of n-heptane to toluene

[0047]



[0048] In Fig. 9, liquid n-heptane 601 is metered via 602, 603 into the vaporizing chamber 604 held at 150°C. Toluene in the gas phase is conveyed to the catalytic reactor 605 containing a packed bed of Pt-Al<sub>2</sub>O<sub>3</sub> catalyst held at 400°C. Hydrogen is removed through line 606. The heptane-toluene mixture from reactor 605 is fed to separator 608 with toluene being removed through line 609 and heptane through line 607.

[0049] Although the invention has been described in conjunction with the specific embodiments, it is evident that many alternatives and variations will be apparent to those skilled in the art in light of the foregoing description. Accordingly, the invention is intended to embrace all of the alternatives and variations that fall within the spirit and scope of

the appended claims. Further, the subject matter of the above cited United States Patents are incorporated herein by reference.

5 **Claims**

1. A method of performing a predetermined chemical reaction using at least one reactant and a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising:

10 providing a support structure having a plurality of prearranged flow connections;  
selecting the plurality of reaction system components;  
assembling the plurality of selected reaction system components onto the support structure; and  
performing the predetermined chemical reaction to form one or more reaction products,  
15 wherein the plurality of reaction system components are selected and arranged to accommodate the predetermined chemical reaction.

2. A method of performing a predetermined chemical reaction using at least one reactant and a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising:

20 assembling the plurality of reaction system components;  
providing the at least one reactant to one or more of the reaction system components;  
reacting the at least one reactant in one or more of the reaction system components such that one or more reaction products are formed; and  
25 collecting the one or more reaction products.

3. The method according to claims 1 or 2 wherein at least two of the reaction system components operate in series.

4. The method according to claims 1 or 2 wherein at least two of the reaction system components operate in parallel.

30 5. The method according to claims 1 or 2 wherein one or more reactants are provided to two or more of the plurality of reaction system components operating in parallel.

35 6. The method according to claims 1 or 2 wherein one or more reactants are provided to two or more of the plurality of reaction system components operating in series.

7. A method of performing a predetermined chemical reaction using at least one reactant and a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising:

40 providing a support structure;  
providing a plurality of flow connections;  
selecting the plurality of reaction system components;  
assembling the plurality of selected reaction system components and the plurality flow connections onto the support structure; and  
45 performing the predetermined chemical reaction to form one or more reaction products,

wherein the plurality of reaction system components and the plurality of flow connections are selected and arranged to accommodate the predetermined chemical reaction.

50 8. The method according to claims 1, 2 or 7 wherein the reaction products comprise intermediate and/or final reaction products.

9. The method according to claims 1, 2 or 7 wherein the reaction system components are selected from the group consisting of fluid flow control devices, mixers, reactors, separation devices, detectors and controllers.

55 10. The method according to claim 9 wherein the fluid flow control devices are selected from the group consisting of pumps, flow channels, manifolds, flow restrictors and valves.

11. The method according to claim 9 wherein the mixers are selected from the group consisting of static and ultrasonic mixers.
12. The method according to claim 9 wherein the reactors are selected from the group consisting of thermal, electro-chemical, photochemical, enzymatic, catalytic and pressure reactors.
13. The method according to claim 9 wherein the separation devices are selected from the group consisting of membrane, concurrent flow extraction, countercurrent flow extraction, chromatographic and distillation separators.
14. The method according to claim 9 wherein the detectors are selected from the group consisting of electrochemical, spectroscopic, fluorescence and mass-based detectors.
15. The method according to claims 1, 2 or 7 further comprising monitoring one or more of the reaction system components.
16. The method according to claim 8 further comprising monitoring one or more of the reactants and reaction products.
17. The method according to claims 1, 2 or 7 further comprising monitoring one or more process variables associated with the predetermined chemical reaction.
18. The method according to claims 1, 2 or 7 further comprising analyzing one or more process variables associated with the predetermined chemical reaction.
19. The method according to claims 1, 2 or 7 further comprising selectively controlling one or more of the reaction system components.
20. The method according to claims 15, 16, 17, 18 and 19 wherein the selective control is based on one or more results obtained from the monitoring of one or more of the reaction system components, the reactants and/or reaction products, and the process variables.
21. The method according to claims 1, 2 or 7 wherein one or more compounds are synthesized.
22. The method according to claim 21 wherein one or more of the synthesized compounds is organic.
23. The method according to claim 21 wherein one or more of the synthesized compounds is inorganic.
24. The method according to claims 1, 2 or 7 wherein the predetermined chemical reaction is performed serially in the plurality of reaction system components.
25. The method according to claims 1, 2 or 7 wherein one or more intermediate reactions are carried out to perform the predetermined chemical reaction.
26. The method according to claim 25 wherein the one or more intermediate reactions are carried out in series and/or in parallel.
27. The method according to claims 1, 2 or 7 further comprising adding one or more additional assemblies of selected reaction system components to scale-up the predetermined chemical reaction.
28. The method according to claim 27 wherein the additional assemblies are added in parallel.
29. The method according to claims 1, 2 or 7 wherein the predetermined chemical reaction is performed in parallel in the plurality of reaction system components.
30. The method according to claims 1, 2 or 7 wherein the predetermined chemical reaction includes reaction steps that are performed in series and reaction steps that are performed in parallel.
31. The method according to claims 1, 2 or 7 wherein a predetermined quantity of reaction products are formed.

32. The method according to claim 29 wherein a predetermined quantity of reaction products are formed in relation to a number of the reaction system components operating in parallel.

5 33. The method according to claim 31 wherein the predetermined quantity of reaction products is scaled by either increasing or decreasing the number of reaction system components operating in parallel.

34. The method according to claims 1, 2 or 7 wherein the predetermined chemical reaction is conducted in continuous flow mode.

10 35. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed thermally.

36. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed electrochemically.

15 37. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed catalytically.

38. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed enzymatically.

39. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed photochemically.

20 40. The method according to claims 1, 2 or 7 wherein one or more of the reaction products are formed under pressure.

41. The method according to claims 1, 2 or 7 further comprising adding, replacing or interchanging one or more of the reaction system components to perform a second predetermined chemical reaction.

25 42. The method according to claims 1, 2 or 7 further comprising uniformly controlling a temperature of the plurality of reaction system components.

43. The method according to claim 42 further comprising controlling a residence time of the plurality of reactants within the one or more reaction system components.

30 44. A method of constructing a chemical reaction system for performing a predetermined chemical reaction using a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising:  
35 providing a support structure having a plurality of prearranged flow connections;  
selecting the plurality of reaction system components; and  
assembling the plurality of selected reaction system components onto the support structure,  
40 wherein the plurality of reaction system components are selected and arranged to accommodate the predetermined chemical reaction.

45 45. A method of constructing a chemical reaction system for performing a predetermined chemical reaction using a plurality of selectively arranged modular, nanoscale reaction system components, the method comprising:  
providing a support structure;  
providing a plurality of flow connections;  
selecting the plurality of reaction system components; and  
assembling the plurality of selected reaction system components and the plurality of flow connections onto the support structure,  
50 wherein the plurality of reaction system components and the plurality of flow connections are selected and arranged to accommodate the predetermined chemical reaction.

46. The method according to claims 44 or 45 wherein an output of the chemical reaction system is scaled by adding additional reaction system components.

55 47. The method according to claim 46 wherein the additional reaction system components are added in series.

48. The method according to claim 46 wherein the additional reaction system components are added in parallel.

49. The method according to claim 46 wherein some of the additional reaction system components are added in series and others are added in parallel.

50. The method according to claims 44 or 45 further comprising adding one or more additional assemblies of selected reaction system components to scale-up the predetermined chemical reaction.

51. The method according to claim 50 wherein the additional assemblies are added in parallel.

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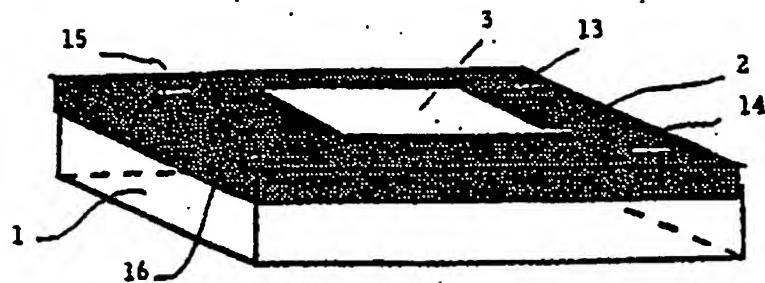


FIG. 1a

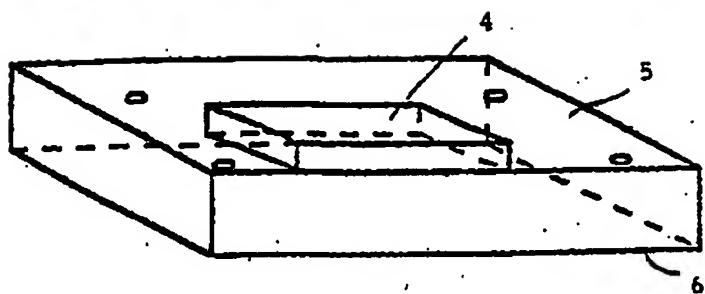


FIG. 1b

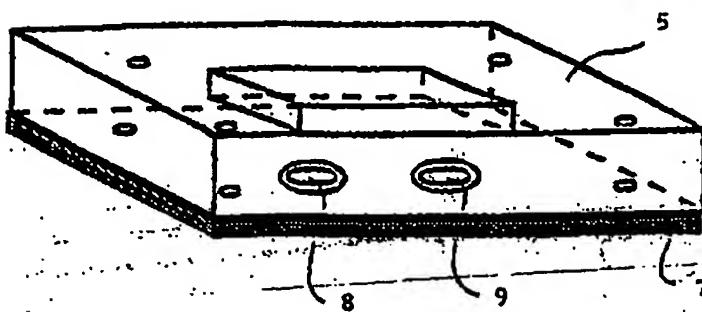


FIG. 1c

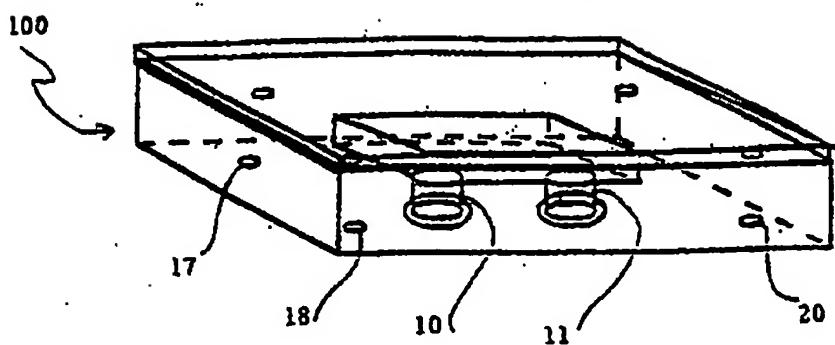


FIG. 1d

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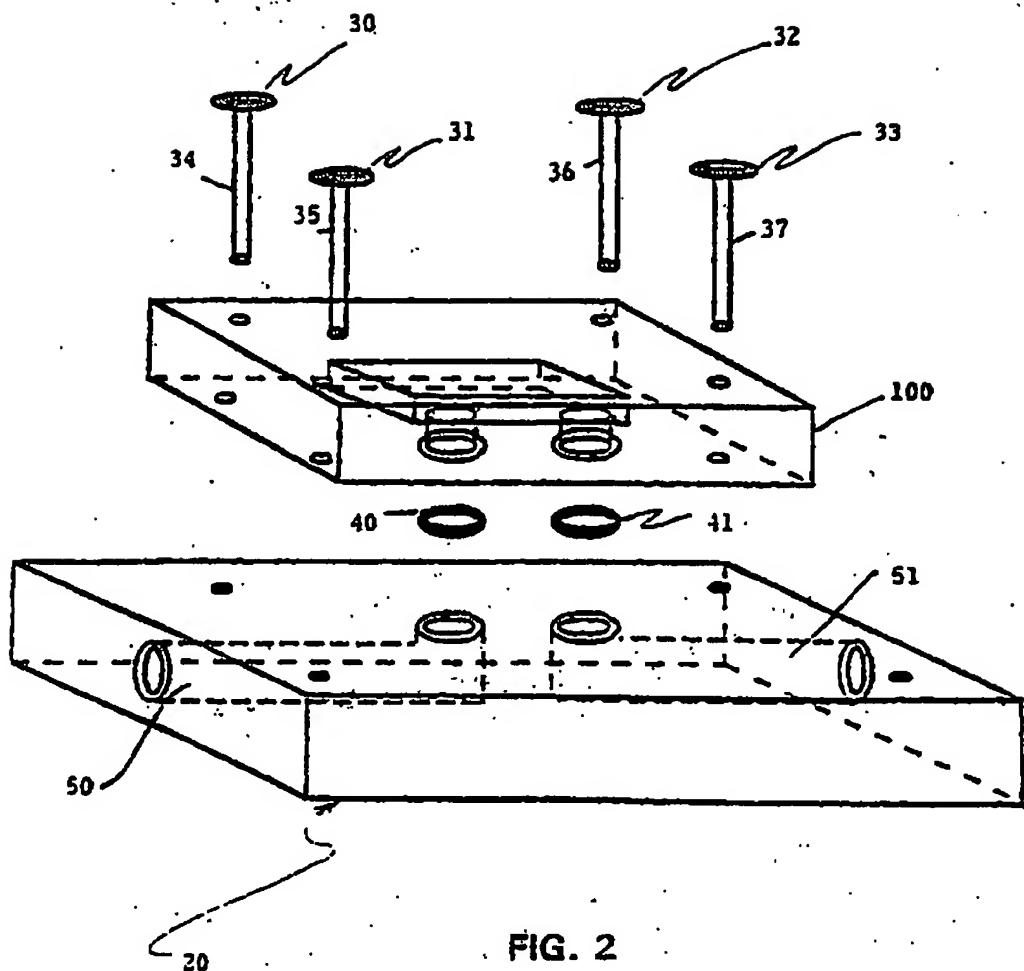


FIG. 2

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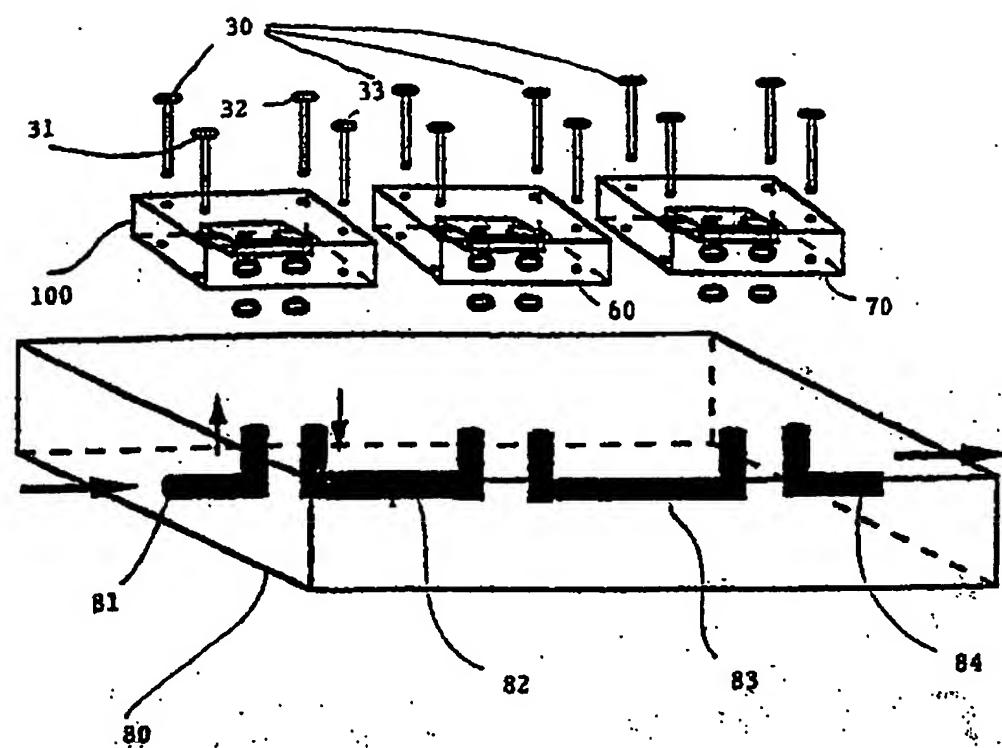


FIG. 3

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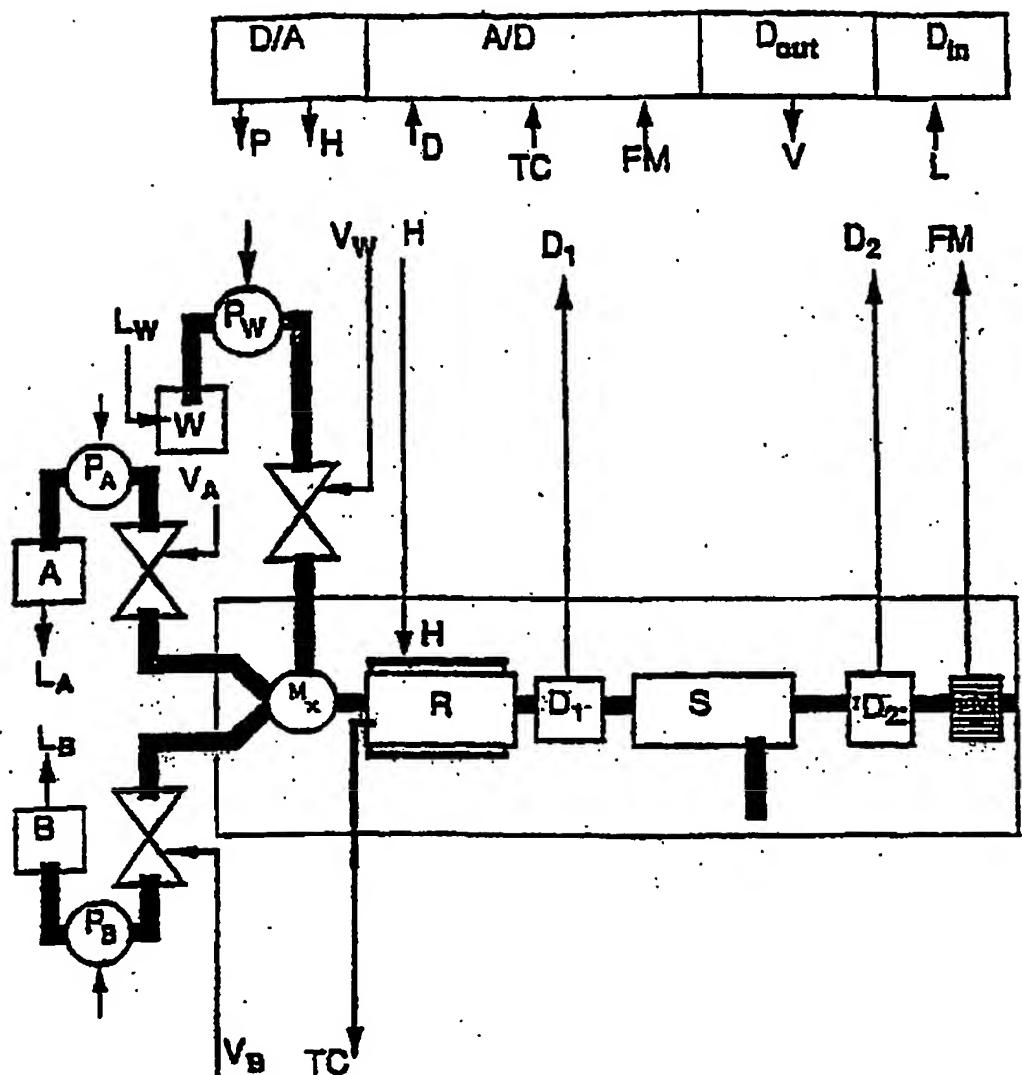


FIG. 4

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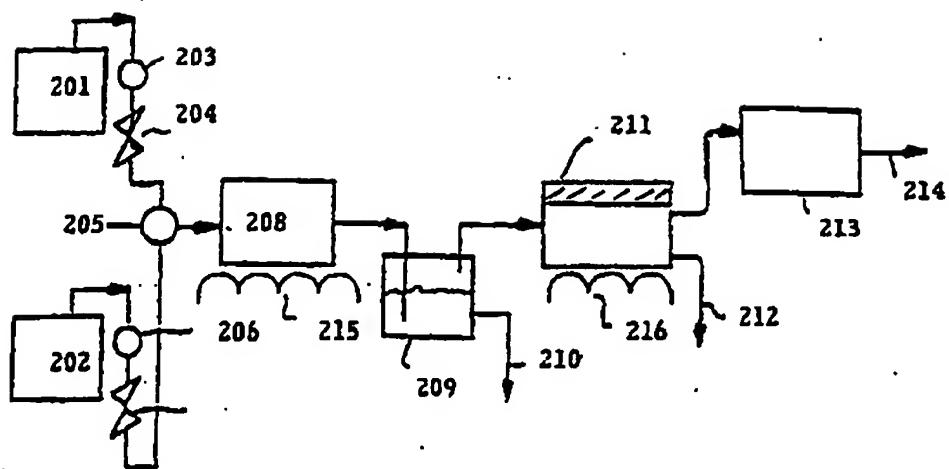


FIG. 5

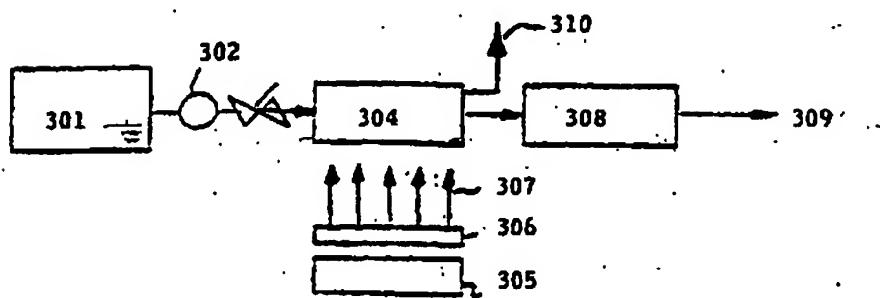


FIG. 6

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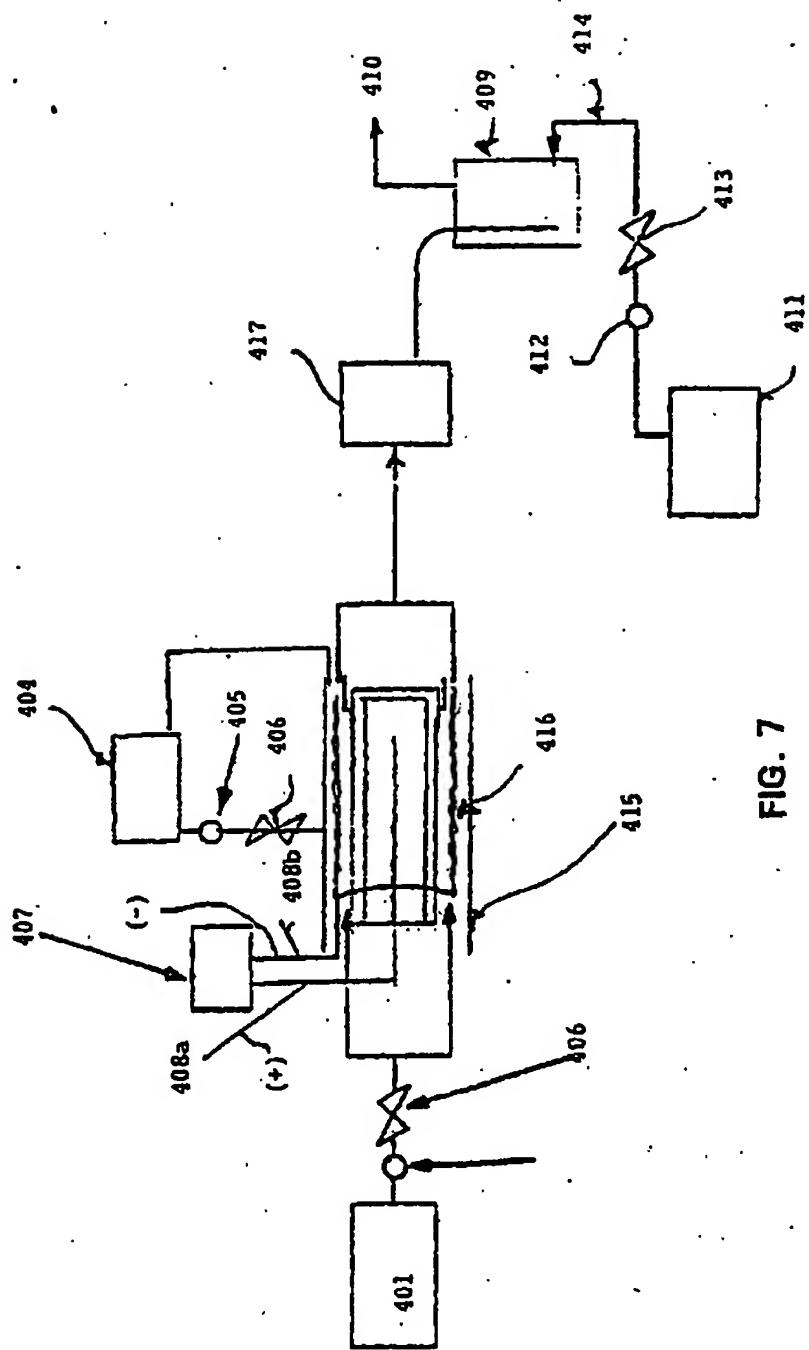


FIG. 7

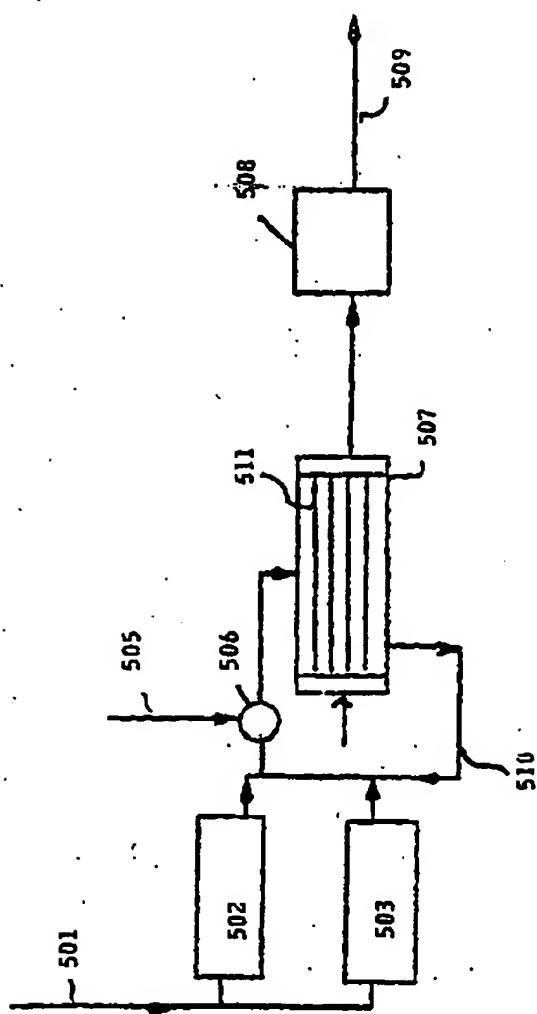


FIG. 8

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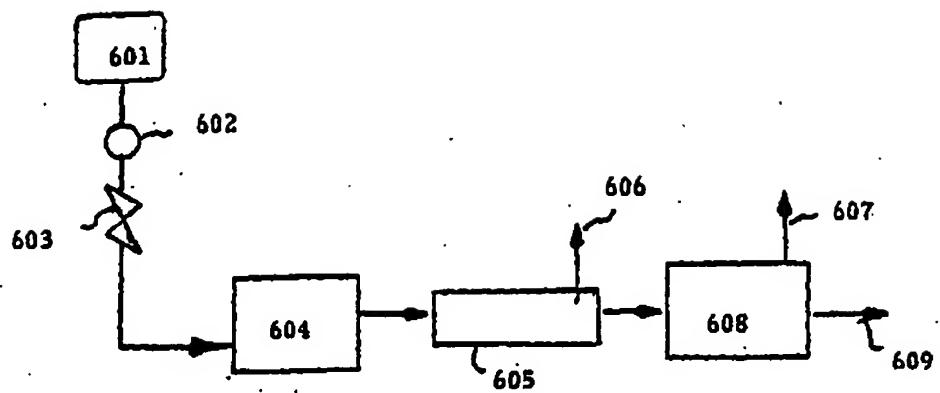


FIG. 9

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